Investigating the robustness of the Anzai respiratory gating system

INVESTIGATING THE ROBUSTNESS OF THE ANZAI RESPIRATORY GATING SYSTEM

BY

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Abstract

This research was undertaken in order to investigate the robustness of the Anzai respiratory gating system. Tests were performed to verify the transfer of image data, to identify the method of gating and the accuracy of phase identification. It was found to have sizeable limitations which could result in either incorrectly gated images or serious artefacts. For these reasons it is recommended it be used under the guidance of a suitably qualified physicist.

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Chapter 1

Introduction

Cancer is a mutation of the body's normal cells that causes particular cells to grow almost uncontrollably, invading and destroying surrounding cells. Cancer is a leading cause of death in New Zealand [25], with lung cancer causing the most cancer related deaths for both men and women in 2009. Lung cancer is often asymptomatic and so patients may not be aware of their disease until the cancer has advanced, making treatment difficult.

There are many different types of cancer affecting different parts of the body and there are many different types of lung cancer, each with their own particular traits [29]. For example, the treatment modality of choice for non small cell lung carcinomas is usually surgery, but this is often not feasible due to advanced stage of disease. While small cell lung cancer tends to be highly responsive to chemotherapy, other lung cancers usually respond well to radiotherapy [29].

Radiotherapy is an effective, non-invasive method of treating many cancers. High energy, ionising radiation is aimed at the tumour with the intention of destroying the

cells and the DNA they contain. The radiosensitivity of tumour cells can be manipulated to be more radiosensitive than normal tissue with the use of dose fractionation.

The amount of radiation required to kill the tumour cells is relatively high and needs to be targeted primarily on the tumour with, ideally, minimal exposure to healthy tissue. In order to provide maximum sparing of healthy tissue for deep seated tumours the radiation beams are spread out around the patient, otherwise the adjacent tissue will suffer serious damage. In distributing the radiation beams over the body it also increases the amount of healthy tissue exposed but reduces the amount radiation incident upon each section of healthy tissue.

The amount of radiation an organ can withstand is a reflection of both the physical limit of the tissue to radiation before cell death, and the limit on the organ volume required for functionality. For example, the lungs have a higher tolerance than the spinal cord as the lung system will still function if a small part is damaged beyond repair unlike the spinal cord.

The success of the radiotherapy treatment is dependent on a number of factors, such as, accurate diagnosis and identification of the disease, obtaining accurate image data of the patient on which to plan the treatment, timely completion of treatment plans which achieve the plan aims and accurate delivery of the radiation to the target. Other important factors include the uncorrupted transfer of data, well trained staff and the radiosensitivity of the disease itself. Of course any tumour can be killed with enough radiation, but, too high a dose may also kill the patient. The goal is highly targeted planning and delivery of the radiation which spares as much surrounding healthy tissue as possible while still achieving the treatment aims.

Once a diagnosis has been determined and the decision to treat with radiotherapy

made, the process begins with images of the patient obtained through a Computed Tomography (CT) scan. The radiation oncologist takes the CT images and marks a contour around the tumour target and the surrounding organs at risk. The patient CT data, along with the target location and prescription from the doctor, is then used to plan the arrangement and relative contribution of the beams to be used during treatment in order to match the dose prescription.

1.1 Computed tomography imaging

Computed Tomography (CT) technology was invented during the 1970s and is based on x-ray technology. A scan is performed by sliding a patient, on a motorised table, through the scan plane of a rotating x-ray tube - detector pair. A sinogram is taken and reconstructed using a back-projection algorithm into a three dimensional image. The effect of translating the patient through the scan plane has the effect of unwrapping the image from the patient in a helical slice of pre-determined width.

The amount of detail resolved with a CT scanner is dependent on a number of factors from patient thickness to the thickness of the slices the image is resolved in. Thicker patients contain more tissue which can scatter the photons and introduce random background noise, reducing the signal to noise ratio. The thickness of the imaging plane is important as the tissue structure is averaged over the image slice thickness. Ideally the narrower the better but this will increase scan times and dose to the patient. A trade off is required so that image slices are narrow enough to allow accurate determination of the structure but thick enough so the dose to the patient is not unreasonably high.

In radiotherapy, CT images are also used for measuring the electron density of

the patient in terms of CT number or Hounsfield unit. The electron density is used for dose calculations.

The reconstruction process is not without flaws and sometimes, or often depending on what is being imaged, these flaws manifest themselves in the finished image. These flaws are known as artefacts. Artefacts can be a result of a number of things from malfunctioning equipment (over or under responding pixels), the object being scanned containing materials which are too dense, such as hip replacements, or a result of the finite size of the voxels.

Voxels represent the finest resolution possible of the CT scanner, just as pixels represent the finest resolution of a digital image. Voxels are the three dimensional equivalent of pixels; a pixel with a depth. Enlarge the image too much and the pixels start to become individually resolved. Each pixel can only represent one colour and in CT, each voxel can only represent one density. This means that a voxel will average the density of the tissue within the voxel. If a particular tissue structure only partially covers the voxel, the density of that voxel will be an average of whatever tissue was included in that voxel of object, which could mean a completely different type of tissue to what was actually present. This is known as the partial volume effect. It can be minimised by using a narrow image slice thickness.

There is a finite number of voxels to cover the region being scanned, or the Field of View (FoV). This FoV can be widened for scanning larger objects or patients and becomes an Extended Field of View (EFoV). The default setting on the local CT scanner is to use EFoV as the non-extended FoV covers only 500 mm; extended this becomes 700 mm. Because the number of voxels is limited widening the field of view is at the expense of resolution of the image object and can lead to image artefacts

which can further degrade the image and reduce its usefulness. Gated CT scans are not able to make use of the EFoV function.

CT scanners are excellent for structural imaging. Bone attenuates x-rays well and so shows up clearly on the CT images. The differences between types of soft tissue in terms of x-ray attentuation are not very great and so can be harder to resolve different types of soft tissue and the presence of artefacts can make this harder. But due to the slice-like nature of CT scans, they are prone to artefacts from patient motion while tumours in the thoracic and abdominal area can be subject to large movements related directly to the patient breathing. This tends to create the illusion that the organ is much longer, or wider, than it actually is as well as giving it a distorted shape.

1.2 Motion induced artefacts

The process of imaging patients for planning assumes the body is static and is well represented by a static image. For some anatomical regions this is true, but others are more of a jumble of moving parts, some moving fast, some slow. Actions such as breathing and ingesting food contribute to organ displacement and deformation. Breathing motion alone can be a potential source for sizable and problematic organ and tumour motion [15, 18, 21, 23] and this is not just confined to the lungs but can affect tumours in organs throughout the abdomen and thorax [14].

Breathing can cause tumour motion of up to 3 cm [14] but average tumour motion is closer to 1.5 cm [32]. The extent and range of tumour motion is shown in figure 1.1. Tumour motion due to respiratory actions is predominantly in the cranio/caudal direction although still present in the left/right and anterior/posterior directions.

Movement in the scan plane, can cause banding artefacts which may distort the shape and size of the tumour. An example of motion artefacts from free breathing during CT can be seen in figure 1.2.

In general the soft tissue contrast from CT simulators is fair but not great. Because of this determining the tumour mass from these CT images can be challenging at times even without motion artefacts. If the tumour is affected by respiratory motion but it has not been accounted for the resulting images can be unsuitable for determining the tumour volume, which is wasteful of both time and resources. For example, the tumour could appear artificially large due to it appearing in slices beyond the 'normal position' of the tumour due to breathing motion, the tumour could be half in a slice causing the density of the affected voxels to be averaged giving a false lung tissue density. Objects which are unusually dense can sometimes give streaking artefacts as a result of beam hardening. The tumour could also be scanned partway between imaging planes causing the voxels to be averaged from the two (or more) tissues present in that particular voxel at the time of scanning, commonly referred to as partial volume effects. Whilst this problem is not exclusive to the imaging of moving organs, it can also lead to the tumour appearing larger than it actually is, as well as blurring what is tumour and what is not.

With a variety of artefacts the object being imaged can appear distorted in size, shape and density. As mentioned previously the CT images are not only used to give a visual indication of the patient's internal anatomy but also provides the planning system with information about the density of the patient in order to calculate dose deposited. This means the now poorly represented and amorphous tumour on the CT image can also negatively affect the dose calculations, as well as mislead the viewer

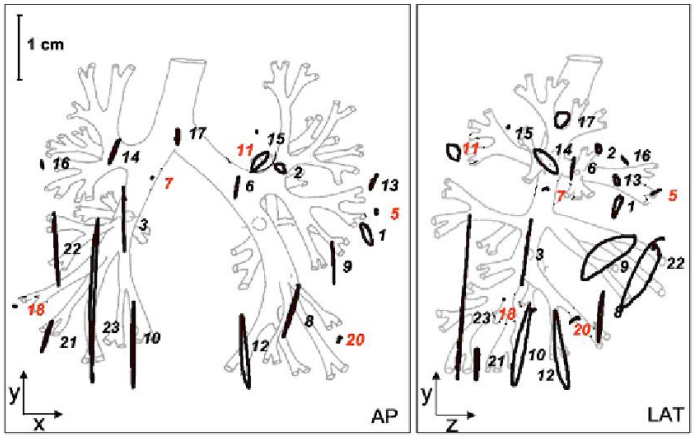

Figure 1.1: This figure from the AAPM report on respiratory gating shows the possible extent of lung tumour motion [30].

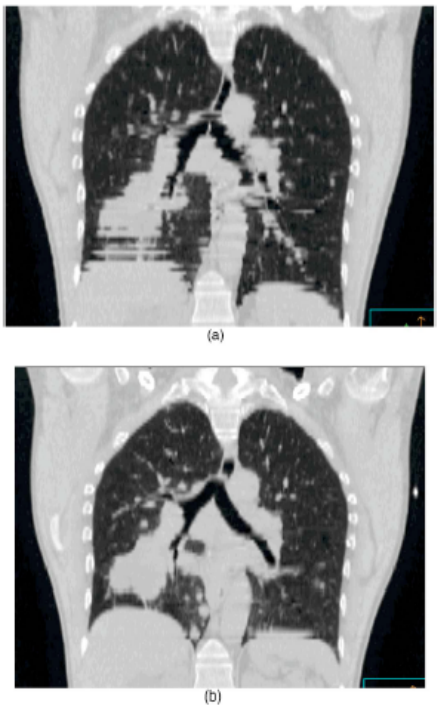

Figure 1.2: An example of motion artefacts from free breathing during CT. Figure a) shows banding artefacts from the unaccounted motion. Figure b) shows the same patient with respiratory gating [17].

as to its size and shape, contributing to less effective treatments.

With the difficulty planning around and hitting a moving target large margins are often added around the tumour to ensure it is irradiated adequately. These larger margins increase the amount of healthy tissue being irradiated as the target volume and increases the risk of normal tissue complications.

Over time, radiotherapy has improved in terms of safety for both staff and patient, treatment outcomes, and scope of application. The improvement of technology has led to the reduction in margins around tumours and surrounding organs at risk. Even determining the margins for individual patients instead of using population based assumptions has led to improved patient outcomes [27].

Alternatives to conformal radiotherapy include Intensity Modulated Radiation Therapy (IMRT), stereotactic radiotherapy (SRT) and radiosurgery (SRS). These include dose painting over the tumour, possibly with rotating beams around the patient. These methods require an increasing level of accuracy and precision, reducing the positional tolerance in patient setup and increasing the demands on delivery. SRS involves highly accurate target location using a physical reference frame. This increased positional accuracy can allow for hypofractionated treatment regimes using an increased dose per fraction. Stereotactic lung treatments require an accurate knowledge of the tumour location in order to confidently allow higher doses per fraction.

Lung tumour motion is largely intra-fraction motion as opposed to inter-fraction motion and in this case, imaging before treatment and re-aligning the patient if necessary may not improve the accuracy of the treatment.

1.3 Respiratory gating

Improvements in radiotherapy imaging and treatment delivery make it possible for smaller tumour margins to be used; it has been reported that radiation can be delivered to an accuracy of within 2mm [19]. But without appropriate patient data on which to plan the treatments and an appropriate method of motion compensation the radiation could be delivered with high precision but either miss the target or fail to deliver the complete dose to the target.

Lung treatments with no motion management have been found to contribute to underdoses of up to 33% [15] by the tumour not being in the target location. In these cases, although the radiation is not being delivered where it is supposed to be, the radiation is still incident on the patient, so they will likely still have the same, if not worse than, expected side effects and complications, but without the benefit of expected tumour control.

Many methods have been tried in an attempt to gain better information on tumour motion and how to correct for it or work around it [28, 12, 31]. Breathing is a complicated motion involving different muscle groups, such as the diaphragm and intercostal muscles [12]. Respiration cycles can vary greatly over time in both frequency and depth [26, 22] and may vary with changing position [29]. Mathematical models have been used for some time [22, 13] in order to work with dose models on tumours moving due to respiratory actions, but there is not yet a definitive method of predicting respiratory patterns and the internal movement resulting from this action. If the respiratory motion is going to be accounted for instead of worked around then the patient's respiration needs to be monitored. Respiratory gating is based on the finding that respiratory motion can be used as an external surrogate for the internal

organ motion [14].

Respiratory motion can be minimised or reduced in amplitude by restricting extent of normal breathing in the form of forced shallow breathing and breath hold techniques. During forced shallow breathing a plate is positioned over the patient's abdomen and slightly compressing it limiting the maximum of inspiration. Assuming the tumour motion is directly correlated to the patient's depth of breathing, breathing shallower would result in less tumour motion [12].

Breath hold techniques involve the patient holding their breath over the time frame of the scan. However, acquisition time for a chest scan can be up to 30 seconds or longer, which could be problematic for a patient with compromised lung function. Repeatability of the breath hold could be an issue so to ensure the repeatability of position there a number of techniques which could be used for this, such as, surface imaging [31], or, biovisual feedback [20].

Other methods of processing respiratory associated movement include tumour tracking using a fluroscopic imaging system such as Exactrac [2]. More complicated systems involve moving the patient in order for the tumour to remain static relative to an external reference, such as with the Hexapod [16], or sliding the couch back and forth in time to the patient's breathing [33].

During respiratory gated imaging the images acquired by the CT scanner are tagged with the relevant phase of the breathing cycle allowing the images to be sorted in the right order post scan, as shown in the diagram in figure 1.3. During gated treatment delivery the system monitors the patient's breathing and switches the treatment beam on when the breathing is within a predetermined range.

Respiratory gating can be either phase based or amplitude based. In phase based

gating the phase of the respiratory waveform is monitored and used as the basis for gating; the start or end points of the respiratory wave are reference points. In amplitude based gating the amplitude of the waveform is monitored and is the key reference.

There are many different systems of accounting for, minimising and removing the image artefacts caused by patient breathing, some are commercially available while others are used for research purposes only. There are two commercially available respiratory motion management systems available which function in a very similar way and both use gating based on a surrogate respiratory signal: the Real Time Position Management (RPM) system from Varian [11] and the Anzai respiratory gating system from Anzai Medical [1].

The Anzai system is deployed with Siemens CTs and linacs to provide respiratory gating functionality of Siemens equipment and this capability is incorporated into the base equipment software. The two systems use slightly different methods to achieve the same outcome of using the patient's respiratory trace, in terms of amplitude or phase relative to time, as a surrogate for tumour motion. Although gating using an external surrogate signal is possibly the least invasive method of gating it still requires a certain amount of patient co-operation and compliance in order to be of benefit and provide optimum results. The Anzai gating system requires the patient to wear a band very snugly around them in order to acquire their breathing signal which some patients could find too uncomfortable, as well as take some instruction with regards to their breathing, and CT scan times on the order of 90 seconds.

Methods such as these are often used with the aid of breath coaching. Breath coaching helps to ensure the patient is breathing at a uniform depth and rate which,

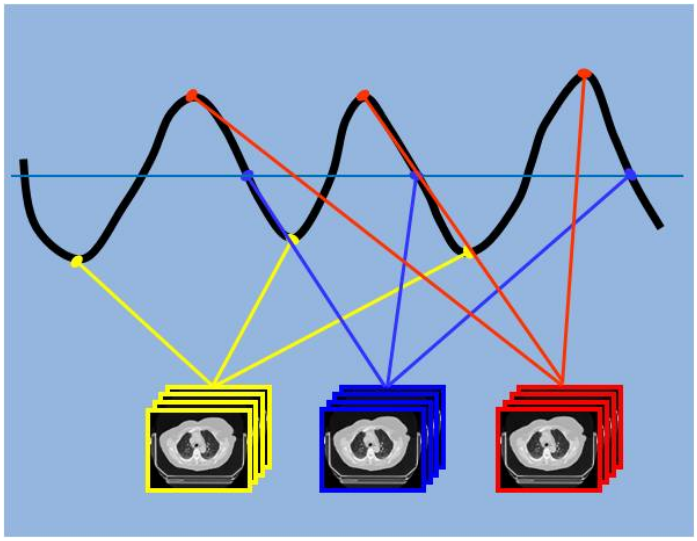

Figure 1.3: The essence of respiratory gating [6].

in turn, would increase the probability of the tumour moving with uniform and repeatable motion in order to optimise the gating procedure. However, breath coaching is not necessarily used with respiratory gating and is not currently used at Palmerston North.

The Palmerston North Hospital Regional Cancer Treatment Service (RCTS) has had an Anzai respiratory gating device, model AZ733V (with load cell) for some time, however it has not been put to full use. It was included in the purchase of the last CT scanner and has since been largely un-utilised, only being used for the occasional palliative lung patient and only in an imaging capacity. The radiation oncologists are starting to want to use it more often, especially with regards to a patient trial using stereotactic body radiotherapy for lung treatments.

As a part of the larger commissioning process the Anzai respiratory gating system requires testing whether or not the system is capable of matching the images correctly in order to perform its gating task. A phantom is provided for quality assurance but

it is only capable of two movements; a sinusoidal wave and a 'pseudo respiratory wave'. Both set movements are in the longitudinal direction and offer a very limited range. The purpose of this research is to verify that the Anzai respiratory system is actually doing what it purportedly does.

1.4 Thesis outline

The purpose of this research was to explore the Anzai system and to verify the accuracy of the gating system in reconstructing gated images. The equipment used to do this is covered in Chapter 2. The results from the investigation are presented in Chapter 3. Chapter 4 presents a discussion about what was found, possible reasons for this and perhaps further areas for research and finally, Chapter 5 presents the conclusions on the research.

Chapter 2

Equipment

This research was carried out using mainly equipment and tools available in the department. The major exception to this is the phantom which was ordered, and subsequently re-purposed, especially. In particular, the equipment included the radiotherapy departmental CT scanner, a Siemens Emotion 6 computed tomography simulator (Siemens Medical, Erlangen, Germany), and the Anzai AZ733V gating system (Anzai Medical Co. Ltd, Japan). A respiratory phantom was built out of an intelligent moving head light and is controlled using a programme called Daslight which uses the DMX communication protocol. This is covered more thoroughly in section 2.2.

The research component using the CT scanner used a constant peak tube voltage of 130kV. Ungated scans used the radiotherapist thoracic scan protocol with the slice width changed from 4mm to 2.5mm. Gated scans were performed using a particular gated protocol called '01Resp', the same one which is used according the radiotherapist protocols for gated scans. These protocols were used in the testing phase in order to test the system in a manner similar to that which it will be used.

The maximum scan length was 300 mm and the slice width was 2.5 mm. The CT protocols used include a feature called 'CareDose'. This function analyses the thickness of the patient, as found in the topograms, and adjusts the mAs used to reduce the dose. As the thickness of the phantom is uniform along the scanned section it was deemed irrelevant. There was no noticable difference between images taken with and without this function being used.

The maximum field of view for gated scans is 500 mm, that is, gated scans are not possible with an extended field of view (eFoV). The diameter of the phantom is such that it can be adequately imaged, if well placed, by a 500 mm field of view scan.

2.1 The Anzai respiratory gating system

The Anzai AZ733V system uses a respiratory signal as a surrogate for tumour motion. The system is comprised of the load cell, sensor port and wavedeck units and is shown in figure 2.1. The respiratory signal is procured from a small load cell which is placed in an elasticated belt which goes around the patient between their xyphoid process and waist. The belt is worn snugly so as the patient inhales, the pressure increases on the belt and the sensor. The signal is relayed back to the control unit, which is connected to the CT and the respiratory wave is shown on the CT control monitor. The images seem to be tagged as they are acquired, with the images grouped into 'bins' for each segment of the breathing cycle. The Anzai software has a sampling rate of 40 Hz.

In 'gating' mode the Anzai system puts the images into bins corresponding to different stages of the breathing cycle, for example 50% inhale, but whether this is in terms of phase or amplitude is not immediately clear. This means the images tagged

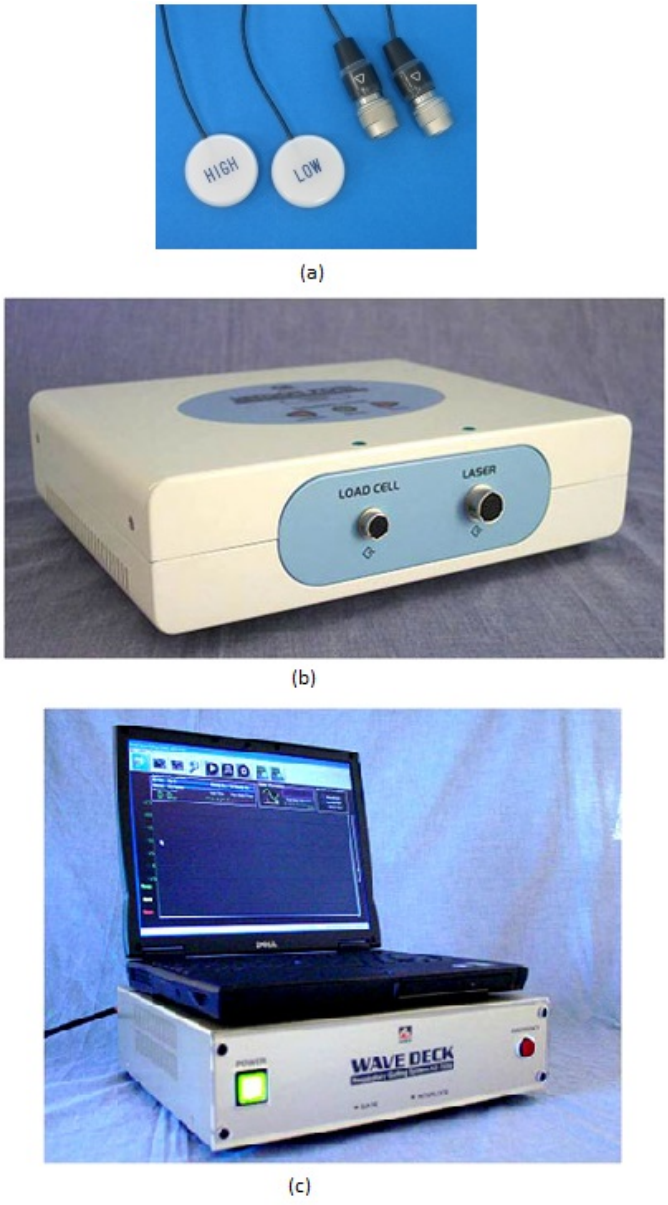

Figure 2.1: The components of the Anzai system: the load cells shown in figure (a); the sensor port shown in figure (b); and the wave deck shown in figure (c) [1].

as being in the 50% inhale stage of any breath can be viewed as one image, giving a clear indication of organ motion over the different phases, thus removing the lung and subsequent tumour motion resulting from breathing. This is also called 'retrospective gating'. This mode has already begun to be used within the department in the image acquisition and planning stages for radical lung treatments in order to view the extent of tumour motion. The reasoning behind using an untested piece of equipment was that the timing of the tumour motion was not important; only the extent of it.

The Anzai system can also be used in 'triggering', or 'prospective gating', mode to deliver a respiratory gated treatment. The patient wears the elasticated belt with the load sensor during treatment and when the sensor measures the patient's respiration is within a certain predetermined range it will trigger the radiation beam.

The length of time the beam is on compared to the total breathing cycle is called the duty cycle. Treatments with shorter duty cycles will have a longer delivery time and vice versa. Within the duty cycle the tumour will likely still have some movement, called residual motion, which will vary depending on patient and duty cycle. The current method of delivery in the department would have a 100% duty cycle, meaning that the treatments are not gated. Longer duty cycles have greater residual motion correlating to greater tumour margins. Time and accuracy are traded off against each other in order to reach a solution.

When the system is being used for retrospective gating the system is connected to the CT and the respiratory signal is shown on the CT control monitor. When the system is being used in prospective gating, or triggering mode, the system can operate independently. The signal is instead sent to a laptop computer included in the system set up. The gating software on this laptop shows the respiratory signal

and allows small modifications to be made, such as waveform magnification, as well as make a time stamped record of the data which can be relatively easily viewed at a later time without needing to be connected to either a linac or CT.

It is clear from the obvious expectations of function of a respiratory gating system that it must have some method to determine phase and/or amplitude in order to perform respiratory gating. However, the system will likely only use one as a primary measure and determine the second from this.

It is neither explicitly nor implicitly stated in the manuals as to whether the system is based on amplitude or phase based gating or a combination of both. If the system is based on amplitude then it may not be able to identify the actual tumour motion. It might even be possible for tumour motion with a path more complex than a straight line to be represented as following the same path during inhale and exhale phases if the system is not gating correctly. That is, if the system does not keep track of which phase the image has been acquired in it could potentially show images from an exhale phase with images from an inhale phase, giving a confusing and inaccurate picture. If the system gates based on phase, then it should be able to clearly identify and show a non-linear tumour path, but also requires a robust measure of amplitude.

2.2 The Phantom

A phantom was supplied with the gating system for quality assurance, shown in figure 2.2. It consists of short, cylindrical section, containing three spheres of different density materials in a vertical array, which moves in the horizontal plane and perpendicular to the scan plane. There are two different motion sequences available; either a sinusoidal curve or a 'quasi respiratory curve'. This phantom was not used for this

Figure 2.2: The QA phantom included with the Anzai respiratory gating system. The cylindrical section moves horizontally through the scan plan of the CT while the load sensor is placed in the in the white holder on the rear of the phantom to produce a respiratory wave [1].

research as using the phantom designed to work with the system may not be the best way to test its robustness and is a limited approach to the problem.

It is to be expected that lung cancer patients may have a degree of compromised lung function. This could result in either irregular breathing patterns, in that their breathing pattern is not a repeatable, or a breathing pattern which is a distorted 'normal' pattern. Such patterns could be a result of the body struggling to fill the different lobes within the lungs due to the presence of a tumour. As the phantom which came with the gating system is not capable of such motions it was thought prudent to use one that is.

A few commercial phantoms exist which allow varying levels of input with regards to end respiratory movement mimicking. In these cases prohibitive pricing as well as wanting to retain some input with regards to functionality and design led the author to consider constructing a phantom. Re-purposing a moving head intelligent light was found to be suitable for this purpose. The requirements in designing the phantom were something straight forward to allow the gating output to be investigated and

produce a clear result. There was a desire to keep the phantom straight forward as the project was about investigating the Anzai system, not about building a phantom.

The phantom used has been specially constructed out of a re-purposed moving head intelligent light; a 'Bug tube 2' lighting fixture sourced from Proel [9] via a local distributor. The term 'moving head intelligent light' means that the light is capable of more than the lamp having on and off states; in this case it can be rotated about a horizontal and vertical axis. The original form of this, prior to repurposing, is shown in figure 2.3. These lights are often used in the entertainment industry, are relatively easy to come by and thus are cheaper than an industry specific phantom.

In the repurposing phase the lamp housing was removed and a plate with an acrylic tube mounted to it was mounted in its place. This acrylic tube,'tumour substitute' (TS), constituted the scanned portion of the phantom and it was mounted perpendicular to the CT scan plane. The tube is capable of tilt (vertical) and rotational (lateral) motion which is controlled by two sets of stepper motors for coarse and fine movements in each plane. The movement of the acrylic TS is both the surrogate for the tumour and the basis of the respiratory signal.

The respiratory signal is taken from an extension of the TS (the 'light saber' extension): as the TS moves, primarily, up and down representing the tumour motion, this extention provides the periodic 'respiratory' pressure on the Anzai's load sensor. The elastic belt for use with the system is used as part of the set up and is looped around the extension of the tumour substitute and another acrylic extension from the body of the phantom. The load cell is placed in a small pocket and held against the lower acrylic extension which has been wrapped in bolus to provide positive pressure without damaging the sensor.

Figure 2.3: A Bug Tube 2 [9] moving head intelligent light, similar to that which was repurposed for this research. The light shown here has a red colour filter attached to the lamp housing.

As the TS moves down, the extension moves up putting 'inhale' pressure on the load sensor. When the tumour substitute moves up the pressure is released as the 'exhale' phase. The phantom is not designed to replicate purely vertical or horizontal motion, otherwise this phantom would be no better than the Anzai phantom. It was designed such that the resultant pressure on the load sensor would replicate a respiratory trace. It was also designed in such a way as to have the same action responsible for both mimicking tumour motion and respiratory pressure on the load sensor. The phantom set up used with the CT is shown is figure 2.4.

The phantom has two, stationary PVC tubes (grey tubes) extending through the scan plane of the CT, parallel to the acrylic tube, which are for reference and positioning. As the cross section of the couch changes over its length using it as a position reference was not ideal. The PVC tubes were a 'known' so they could be used to verify the images are being sorted, not moved, and also to measure the movement

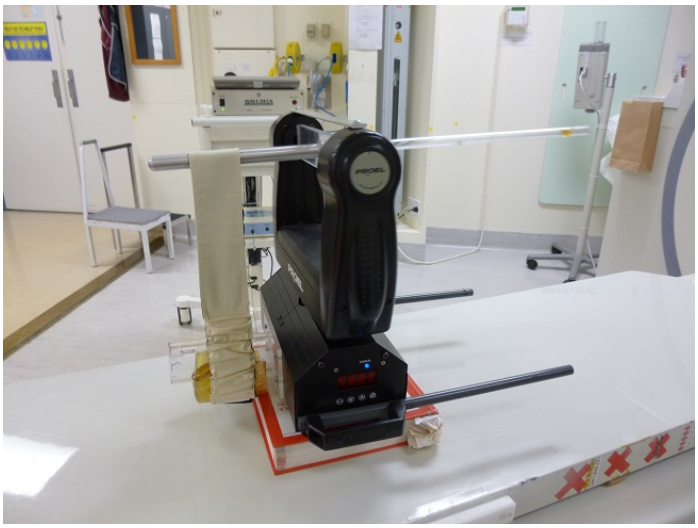

Figure 2.4: The phantom, named Dalek Phan, shown here set up and ready. The metallic'light saber attachment' is mounted to the acrylic plate mounted in place of the lamp housing and extends to the left. The tumour substitute extends to the right from the acrylic placte and is positioned horizontally, extending parallel to the PVC references. The elasticated belt is positioned around the light saber attachment and a further acrylic attachment mounted on the body of the phantom. The sensor is positioned at the bottom and the tension from the belt (created by downward deflection of the tumour substitute) pushes it against the bolus

of the tumour substitute images. The PVC tubes are uniform over their length.

The acrylic tube design is simple as if there is not a lot of material to scan there would be limited material to hide any mistakes in the gating. The motors controlling the tilt and rotation were chosen to move a mass centred on the axis of rotation, not to pull a belt and shift an object centred considerably off axis and so the design was purposely kept as simple as possible.

The phantom itself is controlled by a piece of lighting software called Daslight [4] which was originally intended for controlling intelligent lights . The software has not been edited for this, so there are a few things which are superfluous, such as switching on the now removed lamp. The software was chosen to simplify the task

of programming the movements of the phantom; very little programming skills are required with Daslight and it uses a DMX interface.

DMX, also called DMX512, is an abbreviation of Digital Multiplex [24]. It is an international standard communication protocol, used for controlling automated stage lights and so on, from the Entertainment Services and Technology Association [5]. The DMX protocol has up to 512 channels for controlling a range of equipment using the DMX protocol. Each channel is used for a specific aspect. For example, the phantom used for this research uses 6 channels, one each for the dimmer, shutter, coarse X and Y movement and fine X and Y adjust. Each channel has values ranging from 0 to 255.

By using commercial software it removed 'debugging code' from the troubleshooting list if the phantom was not working. The correct lighting fixture is chosen from a list, the fixture is assigned an address in the DMX universe, and sequences of movements can be easily generated.

Using Daslight the phantom motion can be designed of 'sequences' where one motion can change into another, just as human breathing tends to do. The sequences can be saved and repeated, or the timing of each sequence could be adjusted slightly to produce a different respiratory trace. The phantom can create circles, figures of eight, lines or other, miscellaneous shapes. Although a figure of eight is an unlikely tumour motion such shapes were to be used in order to verify whether the gating is based on amplitude or phase. The programme communicates with the phantom using the DMX communication protocol.

The phantom is controlled by stepper motors which are in general accurate but each repetition is not identical and it is not known why this is. The motors seem

to have a maximum speed which is not accounted for in the control software. If a particular sequence is programmed to 'play' at a higher speed than the phantom is capable of, instead of being prevented by the software the phantom will attempt it anyway. This results in the phantom motion being curtailed; the phantom will move as far as it can in the time it allots itself for the task and then it starts the next component even if it has not finished the previous movement. This is illustrated in figure 3.7. The figure shows the variation in many repetitions of the same movement. Fortunately, in this case this lack of complete repeatability works to the advantage of the research; a device intended for working with a variable movement should not need an exactly repeatable movement in order to work.

2.3 Viewing the data

The data was viewed using a number of different programmes. To begin with the respiratory signal was viewed using the gating section of the CT control software or the Anzai programme on the laptop which came with the gating system. The image sets were viewed using ImageJ [8], CERR [3] and Inspace [10] afterwards.

ImageJ showed the entire set of transverse images from a particular phase at a time. Another programme called 'Inspace' was used to view the images from the same position across all phases. This programme is available from Siemens and runs on the Syngo platform. This is the programme that the radiation oncologists use to determine the extent of tumour motion in deciding tumour margins. Among other functions it has an onscreen ruler as well as a grid which can be overlaid with the images.

The image data was also viewed using Matlab [7] in conjunction with an open

source programme which operated from Matlab called Computational Environment for Radiotherapy Research (CERR). CERR was also used to view the CT DICOM images, but the full capabilities of CERR were not utilised in this research.

2.4 Overview

A phantom has been constructed in order to test the respiratory gating system, instead of using the phantom which came with the system. This phantom utilises some items from outside the medical physics industry, such as the basis for the phantom and the control software. Numerous programmes are to be used to explore and analyse the data once it has been collected. The data is to be collected using both the Siemens CT in the department and the Anzai software included in the system.

Chapter 3

Testing the system

3.1 Verifying a need for gating

To further verify the need for gating images to correct for patient motion, some scans were performed on the moving Dalek Phan with no gating performed. A slice from the first scan is shown in figure 3.1 and shows clearly why gating is needed if there is any significant organ motion; the acrylic tube appears as a spiral in the transverse view. Coronal and sagittal views also show distortions consistent with such unaccounted movement. This is consistent with the images being acquired in a spiral, or helical, manner and is entirely expected. This effect would have been present in the ungated patient data used for planning treatments.

Such distortions are obvious when using simple shapes but these are not so obvious when viewing organs and patients which have non-regular shapes and far more tissue to hide distortions of the object's image. The CT image of the phantom shows the acrylic tube at the top middle of the image. The two lower circles are the reference tubes, their purpose is to provide a solid point of reference to the moving acrylic tube.

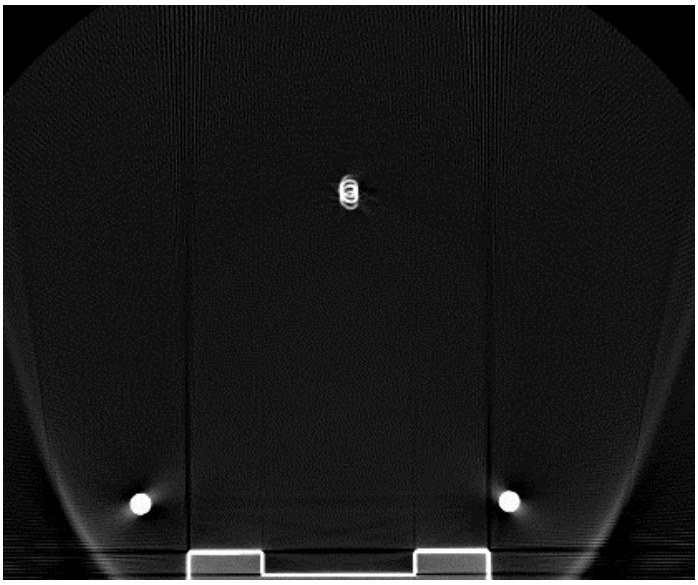

Figure 3.1: The first scan of the functioning phantom.

As the tumour substitute is acrylic, water equivalent, compared to the reference points of PVC, the window and level values have to be altered to even show the acrylic tube. When viewing the data with CERR the window and level settings were set to the preset values for lung.

3.2 Developing the tests

At the start no definitive answers to the question of what the Anzai system did and how it did it could be found. It was a 'black box' where raw information went in and processed information came out. In order to test the processing of the information, the input information had to be controlled and the output analysed to see how it had been changed. The main question was determining what the system was doing. An answer to this would be of benefit in deciding how to test the system. The author realises that for commercial reasons companies do not like to give out specific

information and perhaps it is for this reason that no answers were forthcoming from the physics representatives asked.

The purpose of the research was to investigate the robustness of the Anzai gating system. This required defining what was meant by 'robustness' in the context of a gating system and defining what was in the scope of the research. Robustness was taken to mean the ability to reliably follow a breathing trace correctly and identify the key parts of the trace, namely start and end points. This has a direct affect on the final gated images; if it cannot correctly identify the phase or amplitude it cannot correctly reconstruct the image.

The gating system is currently being used at the Palmerston North Regional Cancer Treatment Service (RCTS) during image acquisition for radical lung patients to show the extent of lung tumour movement. As mentioned previously the radiation oncologists are wanting to move towards stereotactic lung treatments and this is considered a good first step towards that. The system has been given the go ahead in this capacity under the assumption that this does not necessarily require the system to be accurate in its identification of phases or amplitude as timing of movement is less important than the actual extent of the movement.

The author set out with the aim of investigating the system in an imaging environment and moving onto a treatment environment if time allowed. But another hindrance arose in that the gated treatments are only possible on two of the department's five linacs (the 'Oncor' and an 'Artiste') and this capability was not currently functional, taking approximately a week to set up. As neither the department nor the service engineer were willing to put a week into this only gating of imaging is covered. However, the system has the same basis in either case and so even though more work

will be required prior to commencement of gated treatment the groundwork is covered here.

The CT component of the respiratory gating system has 13 different gating protocols. The radiation therapist (RT) protocol book states that the '01Resp' protocol is to be used for all radical lung patients and so for simplicity this protocol was tested. Other protocols are included for low, medium and high respiratory rates but were not investigated as part of this research. The gating system came with two load sensors for measuring the patient's breathing signal; one labelled 'high' and one labelled 'low'. These are shown in figure 2.1. Only the 'high' sensor was used, again as the use of this sensor is already part of the RT protocol for gated CT scans.

This research assumes that the CT is already functioning within QA specifications. That is, communication between CT and network, geometric accuracy, signal-to-noise ratio, contrast resolution and so on have already been verified as well as being routinely tested and so are not part of this research.

The phantom which came with the Anzai respiratory system is capable of two possible motions; sinusoidal and pseudo respiratory and figure 3.2 shows the pseudo respiratory waveform. As the name indicates this waveform is an approximation to a patient breathing trace. In comparison figure 3.3 shows one possible respiratory trace from Dalek Phan. It is also has a regular frequency but it includes small pauses in the breathing phase which occur with actual patients but are not able to be replicated by the Anzai phantom.

These small pauses, or plateaus, seem to be causing some problems with regards to the image sorting. This will be discussed in more detail further on. These images of the respiratory traces were photographed directly off the control monitor of the

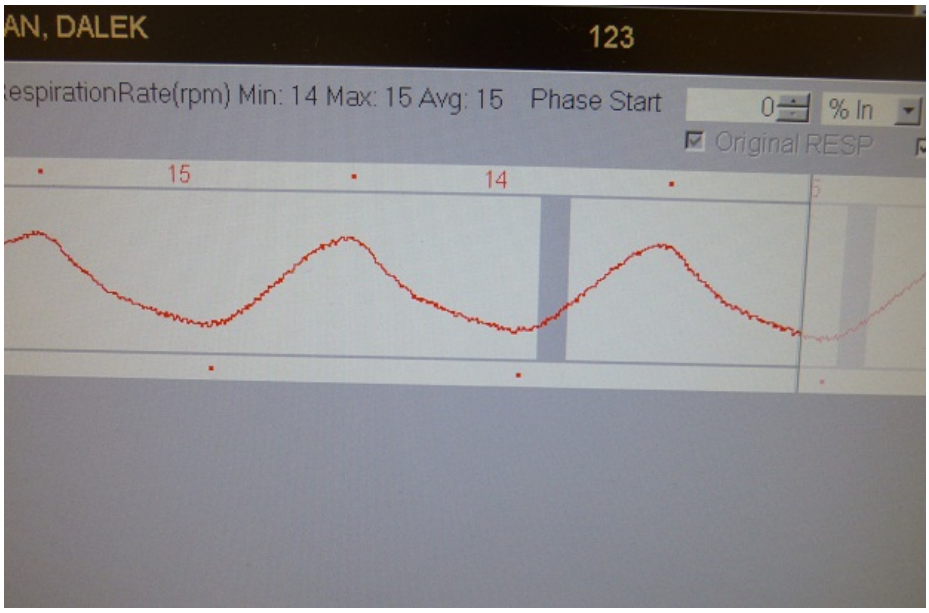

Figure 3.2: The pseudo respiratory waveform produced from the Anzai respiratory phantom.

CT scanner, as it was the simplist way of reproducing all the information regarding end phase tags, respiratory level and phase identified.

At the outset the research plan was to run the phantom in different modes over multiple CT scans and analyse the resulting images. This analysis meant observing the gated images in a phase sequence slideshow and then measuring the differences in position of the images which did not fit the pattern.

The phantom was first used in a simple pattern with the intention of making the pattern more and more complex, adding several different patterns sequentially to better mimic human breathing with the goal of finding a pattern to which the gating system gave a 'silly answer'. This would be an image obviously out of the expected sequence. The expected image sequence was determined by what the phantom movements were and then imagining a snapshot of the phantom at various points in its

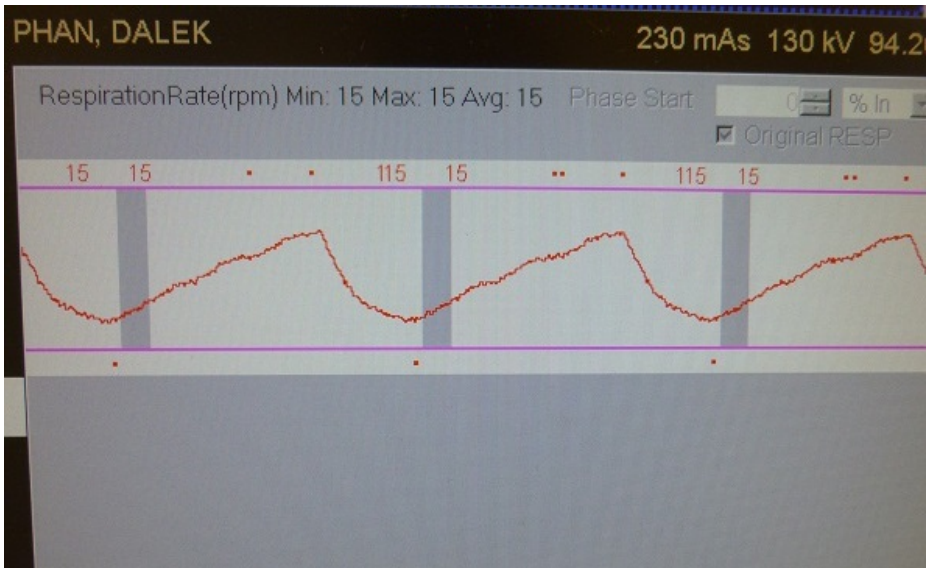

Figure 3.3: The red line shows one possible respiratory trace from Dalek Phan.

'breathing cycle'. The phantom pattern which gave the apparently silly answer would be investigated for a reason leading to the fail, hopefully providing some information with regards to what the gating system is doing.

Also shown in figure 3.3 is the amount of noise in the respiratory signal. The belt was tightened as much as possible while still allowing the phantom to move without causing it to skip. From observations of radical lung patients' respiratory traces during their CT scans this is a comparatively low level of noise.

3.3 First tests

The first scans were completed with the phantom moving in a short line in an approximation to vertical. This was not a uniform, simple harmonic type motion. Instead, the speed was varied throughout the cycle to give a realistic respiratory waveform. The line also changed very slightly each time the phantom was set up due to initial

difficulties with the set up. This meant that images from different sessions could not be exactly compared against each other, although the data collected was still relevant.

The motion of the tumour substitute itself could have been an unlikely motion for an actual tumour. However, as the gating system should not need a realistic tumour motion in order to gate the images and produce a reasonable answer so this was accepted.

As previously mentioned there were some slight repeatability issues even between adjacent cycles. This meant that the phantom movement was not 100% identical between cycles, however, the period of the cycles remained constant. The differences in the movements between cycles was on the order of half the width of the tumour substitute (approximately 0.5 cm), occasionally more or less, with occasional differences of approximately one tumour substitute width. This difference was decided to be acceptable as the waveform created was still very uniform. Examples of the resulting respiratory waves can be seen in figures 3.10 and A.1 which show the actual repeatability in respiratory wave.

The initial method of analysis chosen was based on the CT images produced from the scans. These images were to be analysed looking for irregularities in the images. The images could be viewed either by phase with ImageJ and CERR or by position and across all phases with InSpace.

Inspace allows the user to view a slideshow of images from all phases from any position on an XYZ scale as chosen by the user. The software includes a grid which can be overlaid with the images and used to measure differences in position between phases. ImageJ allows the viewer to look at all transverse slices from a scan or reconstructed phase in a sequential manner and has a number of image analysis

tools available. CERR runs through Matlab and allows the viewer to look at the image object through saggital, coronal and transverse views. Originally intended as a tool for comparing radiotherapy plans from different departments its features were somewhat under-utilised. As well as looking for image objects in the wrong place, the CT images were also viewed objectively looking for missing or misplaced data.

During the first gated imaging session two gated CT scans were performed. The resulting images were not as uniform as expected. Each had discrepancies with the position of the imaged tumour substitute. It also became clear that the original plan for comparing images would be unlikely to yield reliable answers as there was so many artefacts in some images that it became very difficult in places to distinguish between artefact and image object. An example of this is shown in figure 3.4. This amount of artefact was unexpected as the tumour substitute is constructed from acrylic, which has a very similar electron density to water and tissue.

It was difficult in places to determine the extent of artefact generation which stemmed from the images being gated and that which stemmed from the phantom itself. Some segments of the phantom could not even be recognised as phantom let alone used as a reference point. These results raised a lot of questions, primarily, what had gone so wrong? Further gated scans were performed but none had the same extent of artefact and distortion of the image object.

Beyond the artefacts in the images there was some obviously wrong image sequences. Figure 3.5 shows one example of the distortion of the image object found in the first two gated scans. This should be a normal coronal view of the tumour substitute (an acrylic tube) and should show a longitudinal cross section, that is, two side walls and an empty space in between. It clearly shows something has gone

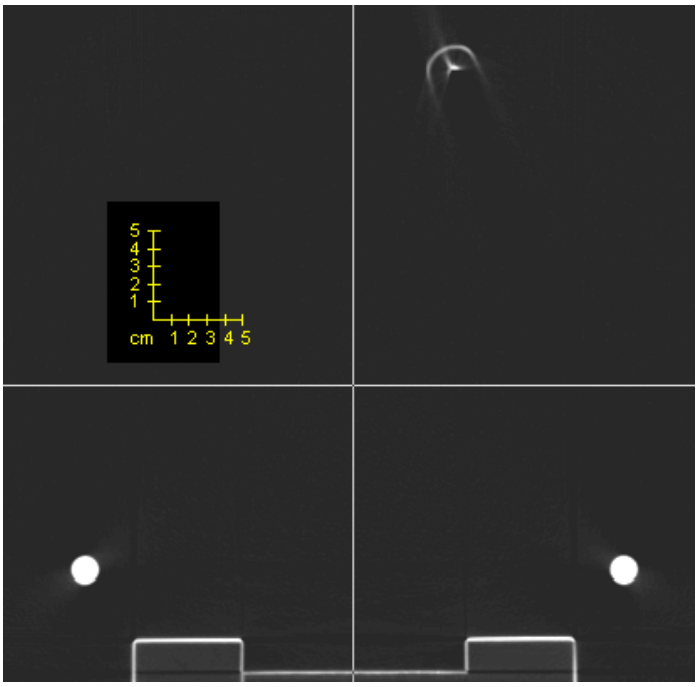

Figure 3.4: An example of the artefacts found in some slices making in difficult to determine image object from noise.

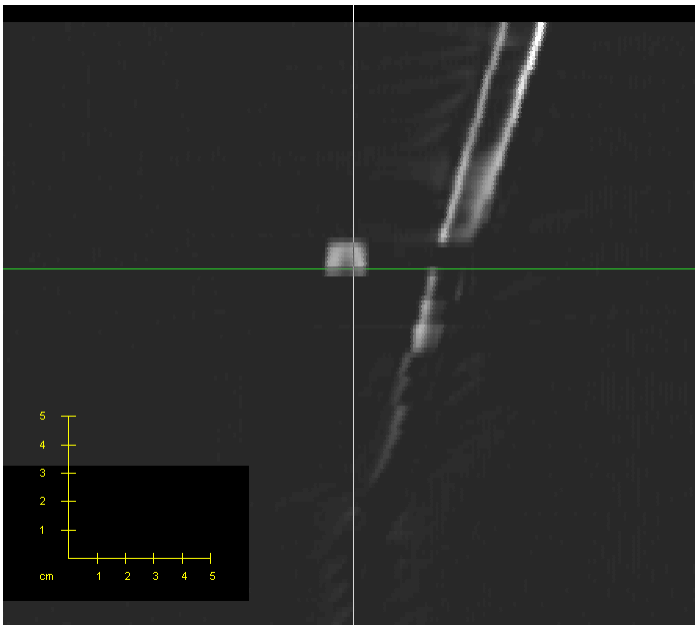

Figure 3.5: The image of the tumour substitute fading out at one location whilst fading in at a new location. Coronal view of tumour substitute.

wrong as the tumour substitute image has a considerable disjoint part way along, in which a segment of the tumour substitute (TS) appears a couple of centimetres to the left of the rest of the TS image. This result most certainly fits in the category of 'a silly answer' but it was not clear about the cause. As this was one of the first scans completed it was surprising to find the system had apparently failed so easily and quickly.

One immediate theory was that the non-uniformity of the phantom movement had had a greater affect than anticipated. Further investigation using ImageJ revealed the individual phases with abnormalities were 20%, 50%, 80% exhale and 100% inhale, as shown in figure 3.6. The remaining phases all appeared normal when viewed transversely slice by slice. In phases 20-80% exhale the abnormalities began at slice number 46, out of between 131 and 133 slices, and ended between slice number 52 and 53. The 100% inhale phase has two regions with abnormalities, one coincides with the aforementioned one showing in the other phases, the other occurs in slices 25-30 and is much smaller though still distinct from artefact.

As the transverse images show the ghost images fade in while the object images fade out at the same time. This would suggest that it is not as a result from the non-uniformity of the phantom movement, as the tumour substitute could not be in two places at once. The section of the disjoint is still uniform over the length (approximately 1.5 cm in length, given the slices are 2.5 mm wide) as is the rest of the image object. If it were a result of the phantom non-uniformity the ghost images would not be limited to one particular region of the scan but more likely distributed randomly throughout. Another graph of the wave form produced by Dalek Phan is shown in figure 3.7. This graph shows each wave form for a particular scan overlapped

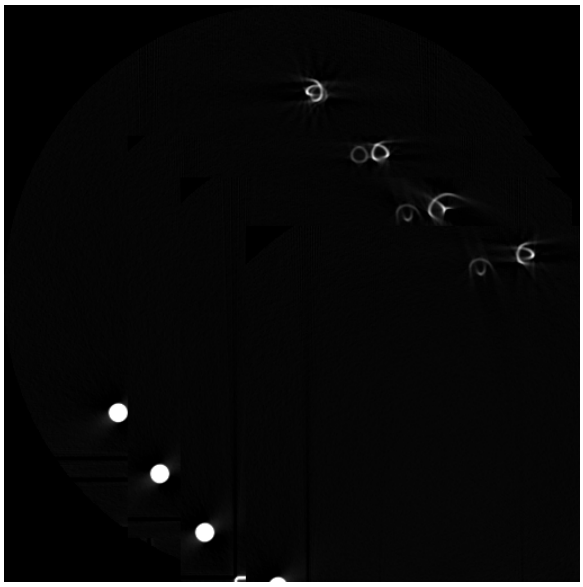

Figure 3.6: The distortions in the four phases. From top to bottom: 100% inhale, 80% exhale, 50% exhale and 20% exhale with the greatest distance between object image and ghost image of object.

on itself; Dalek Phan is actually very repeatable in action.

Moving through slices from the same phase the TS image tracks slowly towards the left overall. In the regions of the disjoint it briefly appears further left before returning to its expected position. But, while looking at the disjointed, 'ghost', images the image still slowly tracks towards the left. Viewing only those few slices there does not appear to be anything wrong with the gating process.

3.4 Taking a closer look

At this point the investigation changed from finding a breathing motion which would cause the gating system to fail to investigating why it failed. Taking a step backwards the author decided to test the system on a stationary phantom to check for missing or

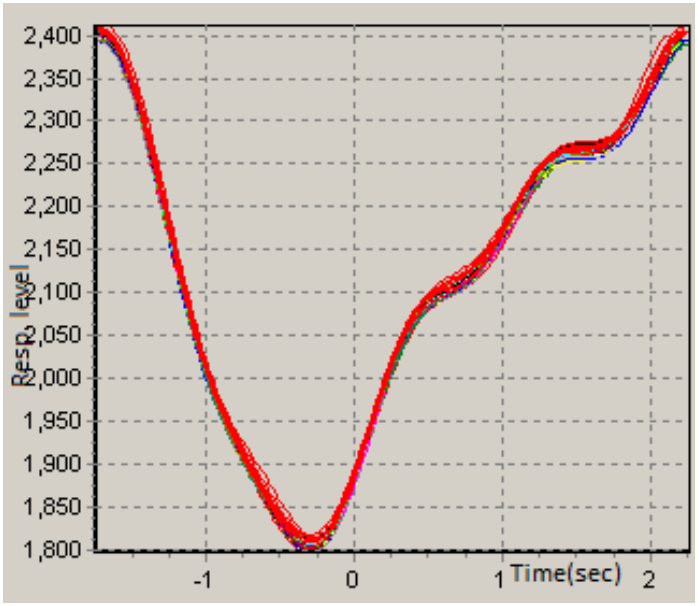

Figure 3.7: A compilation of many wave forms from Dalek Phan plotted on top of each other. A similar plot of the breathing trace from a patient had variations of up to 250 respiratory level units compared to approximately 25 for Dalek Phan.

misplaced data from the reconstructed images. To this end a CT phantom ordinarily used for QA was placed diagonally on the CT couch while the Anzai phantom was connected and the images reconstructed. Placing the phantom diagonally has the effect of the phantom profile moving sideways across the image and makes very clear any sections which have been misplaced or missed out entirely.

The Anzai phantom was used with a sinusoidal respiratory waveform in this test despite the simplified respiratory trace as it was much quicker to set up than Dalek Phan. Any missing data would have led to gaps in the image and any introduced motion from the gating process would also be readily apparent. The fact the object being scanned and gated was stationary removed an element of unknown; as the CT undergoes routine QA (and routinely passes) the only unknown left is the gating system.

Also at this time the phantom was fitted with the 'light saber extension' which helped make the set up more repeatable as well as making the set up easier. This makes use of the belt that came with the Anzai system and is used to hold the load sensor in place against a small amount of bolus. There were some issues with phantom operation to begin with which were overcome. For example, using the initial range of motion for the phantom movements resulted in the phantom skipping due to the introduced limitations. In order to achieve a usable respiratory trace the phantom movements had to be adjusted.

A few times the phantom was accidentally set to move beyond the limitations of the belt. On these occasions the motors would fight the physical limitations of the belt, or other parts of the phantom. No restrictions were set on the movement of the phantom; it could still rotate through 540° in the horizontal plane and 300° in the vertical plane when the TS was not attached. If the TS was attached, as it extended far beyond what the lamp housing did, it would collide with either the body of the phantom or the PVC references.

This did not appear to have any lasting harm to the phantom but whenever this occurred the phantom would be restarted thus allowing the motors to recalibrate themselves. As the motors do not appear to have any secondary positioning feedback it could be possible for the motors to be forced into a new position without the discrepancy being corrected. Restarting the phantom would require removing the TS and the light saber extension to save the phantom from more self destruction, thus increasing the set up time but ensuring some positional accuracy was maintained.

When using the gating system in conjunction with the CT the respiratory waveform is shown on the control monitor in the gating section. This waveform is automatically scaled to give a good picture and show what is happening with the patient's breathing, at times creating a false impression that a small adjustment had a large effect. If the input signal dropped away, either during set up or a scan, a dialog box would inform the user of this.

The cross sectional area of the QA phantom was considerably larger that of Dalek Phan. Because the purpose of this particular phantom is to verify the spatial resolution, amongst other QA aspects, the phantom has different sections of different materials. There were a few artefacts in the regions of the image covering section boundaries based in the slice nature of CT, which were to be expected.

The images were viewed using the Inspace programme which allows a slideshow of the different phases to be viewed for any user selected region of the image object. In viewing the slideshow of phases for this test there appeared to be a small wobble introduced in the gating and imaging process of up to 0.2 cm. However, this was put down to the slice thickness being set at 4 mm, instead of 2.5 mm, for the scan resulting in small jumps between slices when viewing the same region in different phases and the appearance of a wobble. The apparent movement of the image object position will vary with the slice thickness, with thicker slices causing a more pronounced difference between subsequent slices. It is to be expected that observing a series of slices along a diagonal object will lead to some apparent translational movement.

A variation on the above test was performed but this time using three acrylic tubes with diameters ranging from 1 cm to 5 cm. The set up is shown in figure 3.8 and one slice from these scans is shown in figure 3.9. These were also placed on a

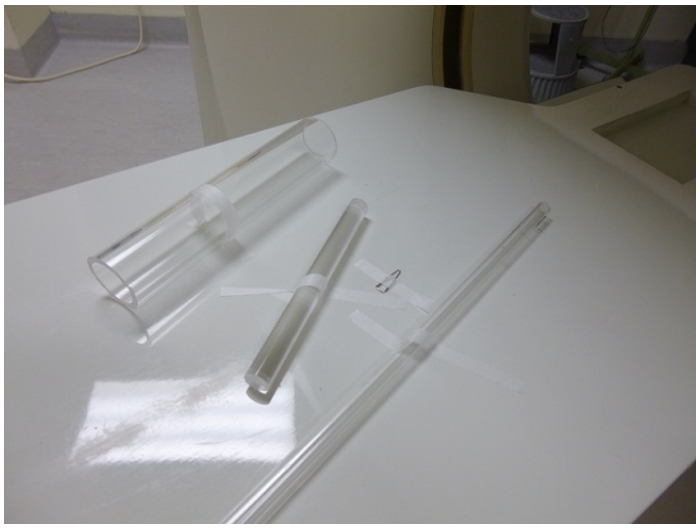

Figure 3.8: The three acrylic tubes taped to the CT couch ready for scanning. The paper clip is a longitudinal reference point.

diagonal and were taped to the CT couch to prevent them moving during the scan. This time the tests were gated using a respiratory signal from Dalek Phan instead of the Anzai phantom. These tests were repeated 10 times to verify the repeatability of the data. This time the tubes were completely uniform along their length so there were no partial volume type effects expected. There were also very few artefacts compared with those seen in the initial scans, which would indicate they were motion based.

These scans showed nothing unusual, but a closer look at the reconstruction process on the CT monitor showed that the system had failed to accurately place the phase tags; the final images looked routine but they were not.

The respiratory waveforms are recorded in a non-image based Dicom file when retrospectively gating with the CT. Image files of the wave forms can be produced when using the Anzai gating programme which came with the gating sytem. Using this programme a 'respiratory curve' of Dalek Phan was recorded. One of the curves is

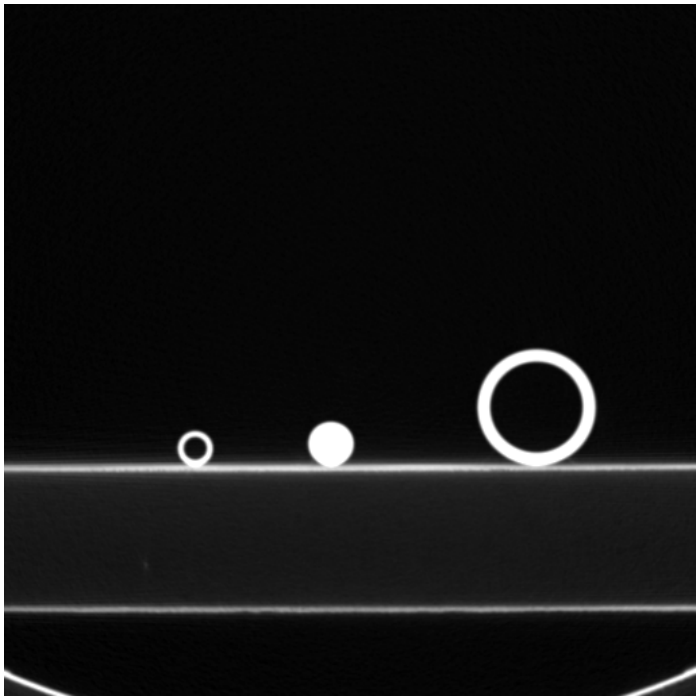

Figure 3.9: A transverse slice from one of the stationary tube test scans. Every slice came out looking just as routine with no artefacts nor ghost images.

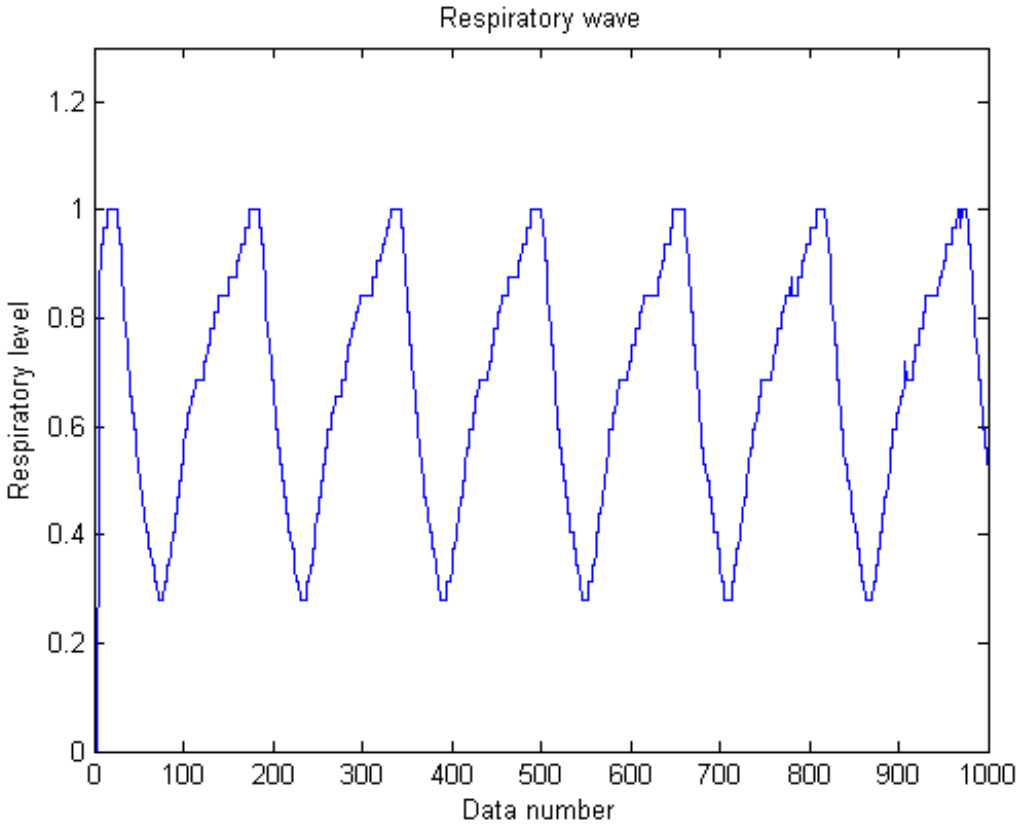

Figure 3.10: A respiratory curve produced by Dalek Phan showing the small plateaus which represent pauses during inhale over a 25 second window.

shown in figure 3.10. The slight variance in movement is reflected in the slight variance in the curve height; more repeatable than a person's breathing, not as repeatable as perhaps a robot could be.

3.5 Analysing the data

The Siemens CT manual gives a slightly better understanding of what the gating system does than the manuals from the gating system. It explains that the red dots above and below the respiratory curve shown on the CT control monitor are meant

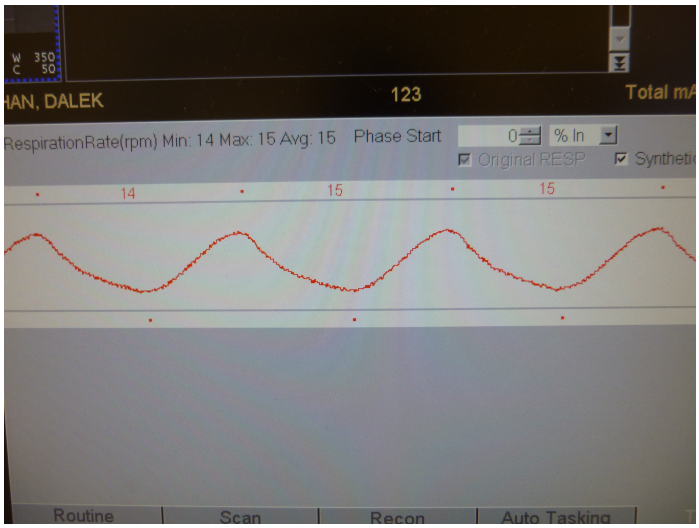

Figure 3.11: A smooth respiratory wave taken from the CT control monitor. The red dots which represent phase end points are well placed.

to denote the maxima and minima of the respiratory curve and thus represent peak inhale and peak exhale respectively. However, when the respiratory curve being used for gating is not a smooth sinusoid there are occasionally some problems with how the software determines these local extrema.

With smooth and uniform respiratory waves the red dots are usually well placed, as shown in figure 3.11. The red dots are above the positions of peak exhale and peak inhale on the respiratory curve. But if the respiratory curve has regions of non-uniformity, such as bumps or noise as could be realistically expected when using gating on any patient, let alone one with compromised lung function, the red dots are sometimes misplaced as shown in figure 3.12. This image shows a red dot (between 10 and 12 on the horizontal time scale) which has been placed mid inhale, marking a plateau during intake as a peak exhale point.

The CT manual also states that the position of these red dots can be edited to give a better reconstruction. When using the gating system in a retrospective gating

Figure 3.12: A respiratory curve with a few pauses in the inhale phase taken from the CT control monitor. Some of the inhale pauses have been mislabeled as end phase points.

capacity this is not a problem, although possibly time consuming, to edit the peak inhale or exhale positions in order to correct the reconstructed image, albeit making up for the deficiencies in the gating system.

It explains that the grey sections on the respiratory wave represent the particular phase selected in the reconstruction tab of the control console. Phase appears to be determined in a simplistic manner based on the position of the red dots. For example, 50% inhale will be halfway between peak exhale and peak inhale. This method assumes the rate of inhale and exhale are linear events with respect to time when this is not necessarily true, but if the pattern is consistent over different cycles it should not be a problem. It also requires the red dots to be positioned accurately.

Referring to figure 3.12 it can be seen that the misplacement of the red dot has led to the grey band for 20% inhale to be placed closer to what is actually 80% inhale which could cause artefacts similar to those found in the first two scans of this

Figure 3.13: This time the reconstruction is meant to be 50% inhale, but due to misplaced end phase tags regions closer to 80% inhale and 80% exhale are being reconstructed as 50% inhale.

research.

Another example of the gating system failing to identify the phases correctly based on the respiratory curve can be seen in figure 3.13. In this image the grey bands are meant to represent 50% inhale regions of the respiratory curve. The bands have been placed halfway between the start and end phase tags, which if the respiratory wave is uniform and the end phase tags are placed correctly is workable. In this case, the waveform is uniform but the small pauses in 'inhale' have confused the algorithm determining end of phase. Small plateaus can be found in respiratory curves of those who have trouble extending the lower lobes of the lungs because of obstructions, such as cancer. Tumours in the lower lobes could also have significant movement as these are closest to the diaphragm and so these patients could have a lot to gain from an accurate gating system.

Both of these examples are based on a respiratory wave from Dalek Phan which

is far more repeatable than a typical patient respiratory wave.

While the respiratory and phase level data was recorded by the CT in a non-image DICOM format, a more usable form of the data could be obtained from the gating system by diverting the signal through the separate computer included with the Anzai system. The data could then be recorded, exported and analysed using Matlab.

The prospective gating programme is fairly simple visually, as shown in figure 3.14. It includes options to scale and move the respiratory curve up or down on the vertical scale. The data is recorded in DAF (Digital Anchor File) format but can be viewed using a simple text editor or spreadsheet programme. The data includes respiratory levels (forming the respiratory trace) and a respiratory phase signal relative to data number, representing time. There are also columns for ECG level and gate but these are zero. This data answered the question of whether the gating system was based on amplitude or phase.

In a short aside, the author tried to obtain an example gating signal based on the respiratory input signal from Dalek Phan. Despite following the instructions the author was unable to produce a gate signal with the programme, shown as the yellow/ green line in figure 3.14. The signal from the signal from the load sensor was diverted to the Anzai computer instead of the CT, where one of four gating modes was, in this case, not applied.

Some old respiratory data was found on the Anzai laptop which the preamble of the data set indicated was gated but, again, the data only included respiratory and phase level with no gate level. An example of this raw data is shown in figure 3.15.

This lack of signal was not investigated as it was not a core item of research and was attempted as everything was already connected with little further set up required.

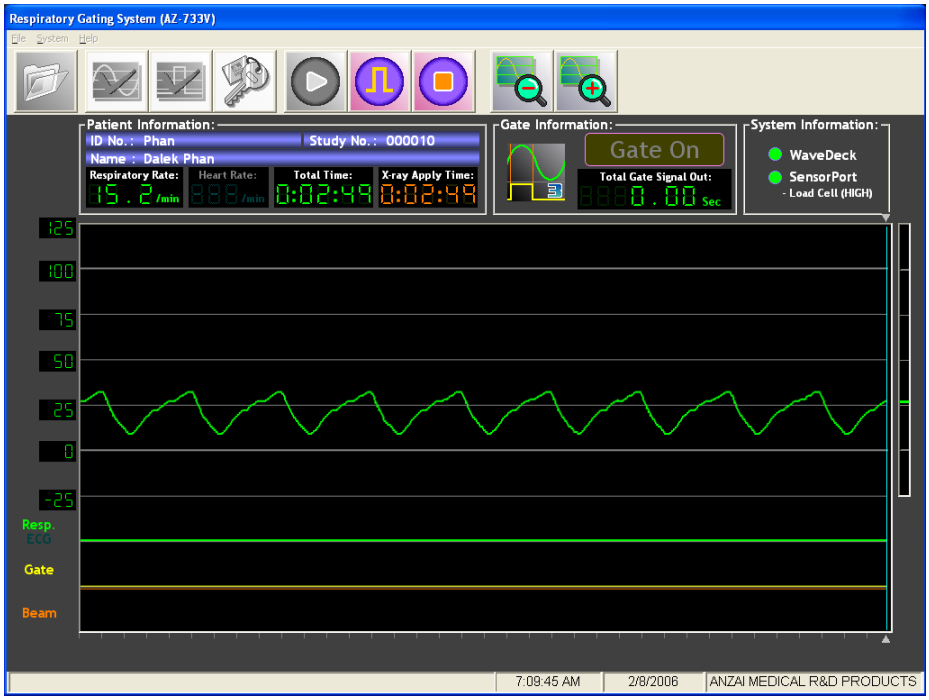

Figure 3.14: A screenshot of the Anzai programme for prospective gating showing the respiratory trace from Dalek Phan.

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"Start(hh:mm:ss):","00:40:06"
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"Sample:",7241
"Comment:"," "
"Data Time(msec):",25
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"Start Point:","In: 80"
"End Point:","Ex: 12"
"All Gate time(sec):","56.90"
"     "
"     "
"     "
"     "
"     "
"     "
"     "
"     "
"     "
"***DataNo., RespLevel, RespPhase, RespGate, EcgLevel, EcgPeak, EcgGate, GateOut, BeamIn, Error Message(Inter Lock)***"
"***Data start***"
0,0,0,0,0,0,0,0,0,"                                                    (0)"
1,-3,1,0,0,0,0,0,1,"                                                    (0)"
2,18,1,0,0,0,0,0,1,"                                                    (0)"
3,40,1,0,0,0,0,0,1,"                                                    (0)"
4,62,1,0,0,0,0,0,1,"                                                    (0)"
5,83,1,0,0,0,0,0,1,"                                                    (0)"
6,88,1,0,0,0,0,0,1,"                                                    (0)"
7,89,1,0,0,0,0,0,1,"                                                    (0)"
8,89,1,0,0,0,0,0,1,"                                                    (0)"
9,89,1,0,0,0,0,0,1,"                                                    (0)"
10,90,1,0,0,0,0,0,1,"                                                    (0)"
11,90,3,0,0,0,0,0,1,"                                                    (0)"
```

Figure 3.15: An example of the raw data acquired from the Anzai programme. This is one of the old data files found on the computer. The first three columns from the left are data number, respiratory level and respiratory phase. The last column is beam in and the zero in brackets is the error message column. The rest, including respiratory gate and gate out columns, are zero.

There are four different methods of gating listed in the instructions but none seemed to generate a signal. Obviously, this would need to be investigated further before using the gating system in a prospective gating capacity.

Not immediately obvious was that the CT keeps a record of the respiratory wave and some other associated data. This data is kept in a non-image DICOM format and not easily accessible; it exists as a file of numbers which are not read by standard DICOM viewers. The chief physicist, Keith Croft, took this DICOM data and ran it through a programme he had written previously to read data out of such files. It revealed the CT samples the data at 50 Hz compared to the 40 Hz from the Anzai system. The respiratory waves were also much noisier as presented in figure 3.16. It turns out that the aspect of the gating system used on the CT scanner is a Siemens

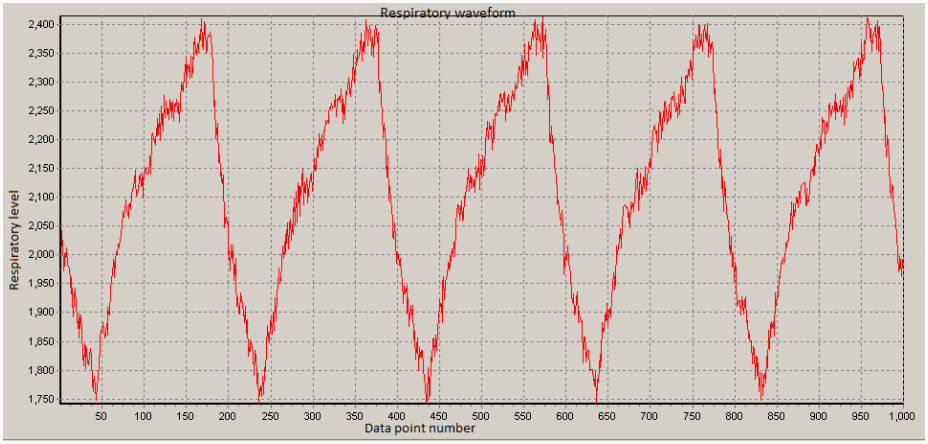

Figure 3.16: A section of the respiratory waveform data from the CT non-image DICOM file. The values on the axes are nominal units of data number and level.

extension to the Anzai gating system, although this was not explicitly or implicitly stated either in the manual or elsewhere.

It appears the respiratory information first goes through the Anzai wavedeck unit before going out to the CT as there is no other method of the respiratory data entering the CT network and the CT requires a gating system to be connected in order to perform the gating; it is not inbuilt. But it is unknown how much processing is done to this data prior to it leaving as the system is a 'black box' with no information of what it is doing and in what order. That the CT data is 50 Hz instead of 40 Hz suggests it is either interpolating more data points or it is receiving the raw respiratory signal for it to process with its own methods.

Some of the extraneous noise in the CT data could have been introduced in the process of getting the data to the CT from the Anzai wave deck unit. But no other data coming from the machine seems to have the same level of noise within it; the images are clear with no data missing. As mentioned earlier the CT is routinely assessed for quality control and there has been no indication that there are large

levels of noise in the resulting images.

The respiratory data acquired from the Anzai programme was used to produce plots of the respiratory trace and phase level plot in Matlab as presented in figures 3.10 and 3.17. The upper plot in figure 3.17 is the normalised respiratory data level against data number and the lower plot is the normalised phase data. Both sets of data were otherwise unprocessed. The system samples at 40Hz so 40 data points represent one second, the period of the wave is approximately four seconds or 160 data points. The respiratory level plot is uniform with very small variances but the phase plot is not as expected.

There are no explanations of what to expect with the phase wave in the manuals but some points can be inferred from viewing the data. It strongly resembles a square wave with changes at the points of peak inhale and exhale but reason for the points/ lines beyond the normal square wave shape is unknown. The noise in the phase wave seems to be due to the noise in the respiratory wave, primarily in the inhale phase.

Despite the noise in the phase signal, the system could reconstruct the images of the static acrylic tubes accurately. The red dots were badly assigned relative to phase end points but because they were badly assigned in a uniform manner throughout the entire scan the final reconstructed images look normal. There seems to be a fine line between the algorithm being able to correctly label the peak inhale points and not being able to and the system does not recognise any error in mislabelling multiple peak inhale points to one peak exhale point; possibly something which could be fixed to improve the performance of the system.

The peak exhale points were being appropriately placed the peak while inhale were not. Instead, for this particular breathing pattern, up to five peak inhale points

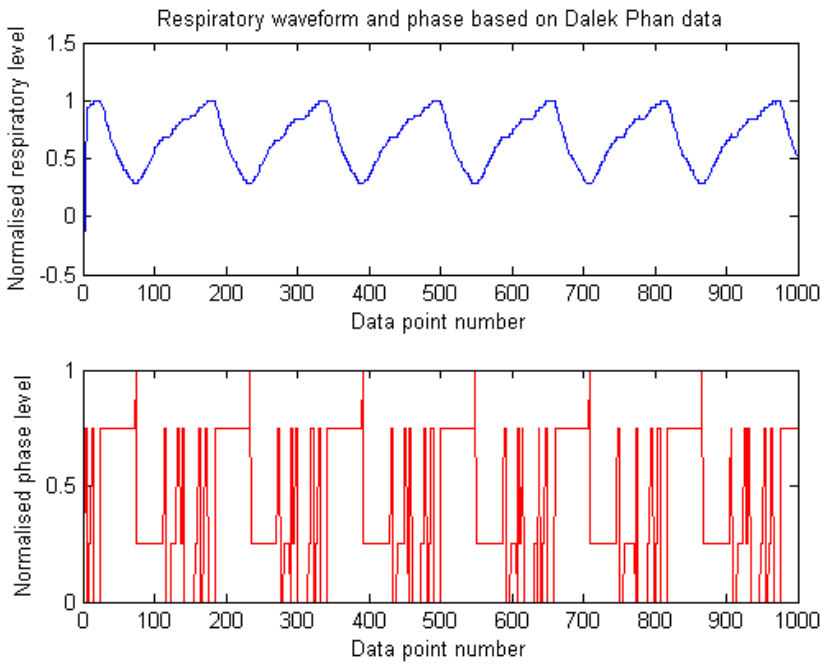

Figure 3.17: Graph using raw data from the Anzai prospective gating programme showing the respiratory levels and phase levels. The top figure is the normalised respiratory wave data and the lower figure is the normalised phase data.

were being labelled whereas only one peak exhale point was being labelled.

Noise in the phase signal appears to be a result of noise in the respiratory signal. Staying with the theme of 'black box' the algorithm responsible for this is unknown. Although it does appear to be limited in the data processing of the respiratory signal prior to deducing the phase signal from this.

Some Matlab analysis was done using some specifically written code and a portion of the output data from the Anzai programme in an attempt to determine the effect of noise on the signal. The code is presented in the appendix. The code took a small section of the data and fitted a first order polynomial to it thus smoothing out the noise in the peak exhale and inhale regions. The amplitude of the respiratory signal was extended in places as a result of this but, as previously determined, the system operates on the phase of the signal so this was not important. The gradient of this polynomial was stored in a matrix and the sign of the gradient was plotted against the original data number, or time. This was taken to be the phase signal. This phase signal was much smoother than the raw phase data, which in places had a better resemblance to a barcode than a squarewave.

This code is fairly simple and uses 30 data points to produce the smoothed plot, or 0.75 seconds of respiratory signal. When used in retrospective gating this should not be too problematic, as long as the images are tagged with the appropriate time stamp, given that there is usually a delay between image acquisition and image reconstruction. As long as the plateaus or other irregularities in the breathing signal are shorter than the length of the smoothing sample they will be reduced producing a smoother gradient and a smoother phase signal which in turn would lead to more accurate reconstructions.

The Anzai system comes with a feature which enables it to 'learn' the pattern of the patient's breathing, just in case there is a signal during a treatment. Even though the CT seemingly uses a slightly different method for retrospective gating than the Anzai system does for the prospective gating, the Anzai system still seems to struggle with phase, as seen in the Anzai data plotted with Matlab. This research was done using version 2.2H of the Anzai programme. Departmental records have no mention of which version of the programme was issued with the hardware nor any information on any upgrades. The old data found was collated using 2.2G.

Chapter 4

Discussion

For this reseach a series of simple tests were performed and the resulting data was collected and analysed. This started with verifying the need for respiratory gating by performing an ungated scan a moving phantom. Next, some gated scans were performed using the Dalek Phan breathing signal leading to an obvious failure of the gating system very early on in the testing phase. Scans of stationary acrylic tubes were performed to check for missing data which could lead to the respiratory system failing. The respiratory waveform data was acquired and analysed using Matlab.

There was an intention to produce multiple 'breathing' sequences with the phantom but this changed when it became apparent that the gating system was less robust than anticipated. Instead the research skipped using alternate sequences as the system had already been shown to fail on a particular respiratory motion and so more time could be given over to investigating why it had failed.

Another area of investigation which did not eventuate is mimicking a coughing motion with Dalek Phan. Originally this seemed to be a good idea as it would not be an unexpected problem for a patient receiving treatment for lung cancer to have

difficulty breathing and perhaps cough during the treatment. However, during a CT scan this would represent a very short amount of the whole and if it looked as though it could cause a problem the scan could be restarted. Likewise during treatment either it would be a small period compared to the delivery time of the entire treatment and if it looked as though it cause a problem the treatment could be paused.

To begin with the results raised more questions than they answered: is this phantom scenario clinically relevant, or, relevant enough for the results to be meaningful? What is going wrong for the system to fail on a seemingly simple reconstruction (a straight line)? Can some hints at what the black box is doing be drawn out of these results? Further investigating revealed some answers: the system uses phase based gating and it does not handle noise very well. This latter point is unfortunate as the elastic belt which came with the system is very difficult to be fastened around a patient tight enough to remove all the noise in the signal. What also became clear is the system seems to use a simple algorithm in order to determine the phase, which does not handle noise very well.

Some problems arose during the testing phase of this research; the phantom turned out to be less reliable than originally expected. This started out as the movements not being 100% identical and seemed to progress to the phantom seemingly losing its positional reference while running, leading to a loss of respiratory signal. In some cases, while observed for about 20 minutes, the respiratory trace from the sensor attached to the phantom morphed from defined waveforms into a blurred waveform (albeit still usable for gating - it still looked a good trace) and then suddenly losing the signal altogether.

This was noted although, for the most part, was not an unworkable problem.

The author kept in mind that the phantom was being used in lieu of a patient's breathing motion and was still comparatively very repeatable. The times when the phantom respiratory trace became unworkable seemed to be related to a small shift in the tumour substitute position and the bolus the sensor belt was using for positive pressure slipped or when the belt itself moved. If the belt were too tight it would restrict the phantom movement causing it to shudder as the motors fought the belt. In these cases the phantom was reset, the belt and bolus readjusted as necessary and the scans restarted.

As mentioned previously, through the research and investigation it was found that the Anzai system uses phase based gating. That is the system monitored, or attempted to monitor, the phase of the respiratory signal in order to use this as a baseline from which to determine the images which were to be reconstructed. This worked well with the phantom which came with the system. However, one particular breathing motion performed by Dalek Phan proved this to not be necessarily true with real patients with less regular breathing motions.

According to Berbeco et al [14] there is no definitive answer for using amplitude or phase based gating, as it depends on the patient, although, patients with irregular breathing could be better off with amplitude based gating. As seen with using the phantom for the respiratory signal the gating system was getting confused with the small plateaus in the breathing cycle. These were being marked as either a peak inhale or peak exhale point which the algorithm kept recognising as a new cycle despite there being no point marking the other extremity in the wave resulting in confusing gated images. Instead of giving a clearer indication of object motion this was actually obfuscating the final gated images as they still were being acquired at

different points in the breathing cycle despite the gating system attempting to prevent this.

The possibility of this incorrect labelling seems to have been taken into account with the CT gating interface in the CT control software as it allows the red phase markers to be shifted to manually select the breathing phases. This is helpful although negates the point of having them automatically selected. Also found during the research was the fact that the CT interface may or may not use the Anzai algorithm for calculating phase and phase end points.

The respiratory waveforms acquired from the CT DICOM non-image files were certainly much noisier than those acquired using the Anzai system directly. This was disappointing that it was unclear where one system began and the other ended, which would have made testing the system more straightforward. As it is, both systems appear to be used in the current departmental gating protocol of gating radical lung patients' scans and is a first step along the way to gating the treatments.

There were also some relatively minor observations from using the gating system. For example, the display of respiratory signal on the CT control monitor is automatically scaled. This made it difficult during set up as a small change appeared to have a substantial effect. The Anzai gating system allows for reconstruction of eight different breathing phases. This is less than other systems which allow up to ten. While eight different phases sounds like a large number, but when looking at hysteresis more phases could be useful, although eight seemed sufficient.

Partway through this research the decision was made to start using the respiratory gating system for all radical lung patients. This was prior to any conclusions being reached regarding the robustness of the system. Using the system to only view the

extremes of position throughout the respiratory cycle was thought to be an acceptable use of the unverified system but it does give the impression that the verification process was only a procedural requirement which was not actually necessary and the research has found that this verification process was valid.

The current protocol for using the gating system states it is to be used for all radical lung patients. Some patients will have more to gain from respiratory gating than others, such as those with tumours in the lower regions of the lung, closer to the diaphragm. One thing missing from the protocol is a determination of those patients for whom it is worth pursuing gating and those for whom it would be too greater demand or those who would simply not benefit, for example those with very irregular breathing.

One point to come from this research is the possibility of introducing breath coaching in order to increase the regularity of breathing patterns. This will hopefully reduce the errors in detecting phase from an irregular breathing pattern. Watching the breathing patterns of patients while having a gated scan is enough of a reason to recommend this even before investigating the system. Having completed an investigation in to the robustness of the Anzai gating system the use of breath coaching in conjunction with the gating as a means of reducing the variability between respiratory cycles should be considered. Obviously, there will be some patients for whom breath coaching will not work and some of these patients may get some benefit from 'uncoached gating' and some that may not, in which case there is little point in putting the patients through a lot of work and stress, not to mention the staffing resources, for no gain.

Breath coaching works to regulate the patient's breathing over the length of the

scan. This not only gives the gating system an easier time of determining and reconstructing the phases but also works to ensure uniform tumour motion over the scan. For example, if a patient is breathing shallower at one point in a scan compared to the rest then the apparent tumour motion over the shallow breathing portion will be an incorrect representation of the actual tumour motion within the patient.

Anecdotally respiratory gating systems can be a little bit unreliable. This research has shown similar. For this reason it would be good practice to have a physicist on hand during any gated CT scans who is familiar with the quirks of the gating system who could identify these errors before they have a chance to negatively affect a patient's treatment.

Chapter 5

Conclusion

This research covered the limited area of the robustness of the Anzai AZ733V respiratory gating system itself, in order to implement this as a tool routinely used in the process of image acquisition for radical lung patients. As the department is looking towards performing stereotactic radiosurgery (SRS) in the future it makes sense to start looking at processes which could be implemented in the present in order to be better prepared, become acquainted with how the systems work and identify issues with gating as they occur instead of letting them become problems to be dealt with during planning or treatment. There are also conclusions to be made following on from the research carried out for this thesis.

Some assumptions were made prior to embarking on any research. The tests were run on the radiotherapy CT and assumed the CT was functioning at an acceptable standard. The CT has a routine QA schedule and had no known problems at the time. Another assumption was the basis of the gating system, that in fact the respiratory signal acquired from the gating system was correlated to and was a fair representation of organ and tumour movement.

In summary of the findings from this research, the Anzai gating system was found to be acceptable in a limited range of breathing patterns. Beyond this limited range it requires close attention to ensure that what the system is actually doing is approximately what it was expected to do. In cases of very irregular breathing the system will fail. In cases of seemingly regular breathing it may also fail. These failures may not even be obvious, as seen with the acrylic tube scans where the system routinely failed to identify the peak inhale but did so in a repeatable fashion thus hiding the error. It seems not unusual for the gating system to have difficulty in determining breathing phase so close attention must be paid to ensure a safe outcome.

The current practise in the department involves the radiation therapists fitting the patient with the load sensor, giving them minimal instruction and following minimal instructions themselves. This is a direct result of the gating process being established prior to any investigation into the gating system itself or the gating process. A recommendation from this research is to have a physicist present during all gated CT scans to ensure accurate data and patient safety throughout the planning and treatment process. This is also a recommendation in the American Association of Physicists in Medicine (AAPM) report from task group 76 on respiratory gating.

Further to this session it would be beneficial to have a gating session with the patient prior to their CT appointment to 1) assess the value of using respiratory gating on the particular patient and 2) allow the patient to become familiar with the process, particularly breathing in a uniform manner. On this particular point it is recommended that breath coaching is used to ensure, as best as possible, a regular breathing pattern in order to produce the best results with the gating system. As stated previously, respiratory gating does require a certain amount of patient

compliance in order to be of benefit. By introducing the patient to the breath coaching system prior to the CT appointment it can negate longer CT appointments being required. This process is similar to that recommended in the report from AAPM task group 76 on respiratory motion in radiation oncology.

The scope of this research was to investigate the gating system in a retrospective capacity. Further research and investigation would be required before embarking on further use of the sytem with regards to patient treatment.

Appendix A

Matlab code

The data to be analysed is first loaded and then broken into component parts.

```
Dat = load ('20060208072028.txt');
DataNo = Dat(:,1);
RespLevel = Dat(:,2);
RespPhase = Dat(:,3);
```

Normalising and plotting the data

```
NormLevel= RespLevel./max(RespLevel);
figure
subplot(2,1,1)
plot(DataNo,NormLevel)
xlim([0,1000])
ylim([-0.5,1.5])
xlabel('Data point number')
title('Respiratory waveform and phase based on Dalek Phan data')
```

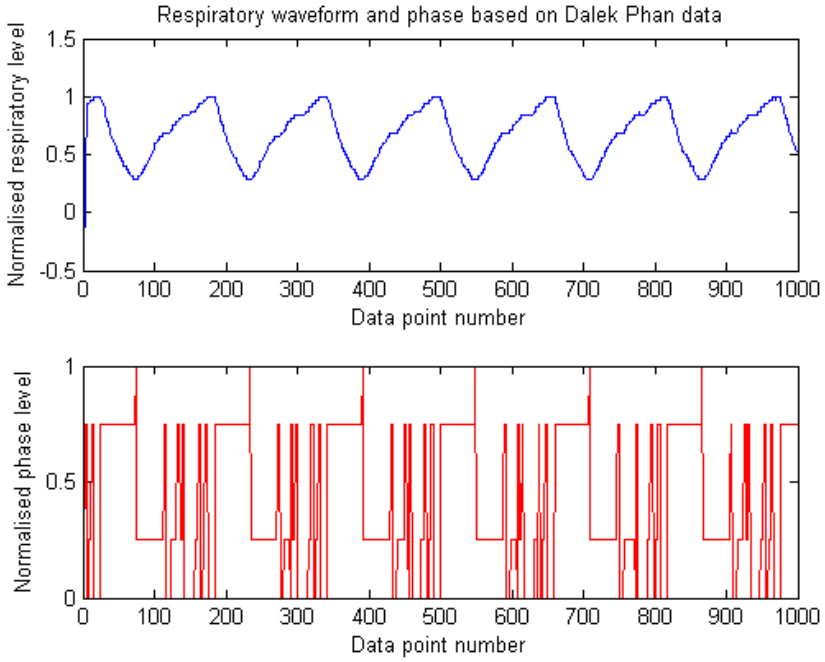

Figure A.1: Graph using raw data from the Anzai prospective gating programme showing the respiratory levels and phase levels. The top figure is the raw respiratory wave data and the lower figure is the raw phase data.

```
ylabel('Normalised respiratory level')

NormPhase = RespPhase./max(RespPhase);

subplot(2,1,2)

plot(DataNo,NormPhase, 'r')

xlim([0,1000])

xlabel('Data point number')

ylabel('Normalised phase level')
```

This is presented in figure A.1.

Smoothing the raw data:

```
fit_points = 30;
```

```
fit=fit_points-1;
Start = DataNo(2,1);
Fin= DataNo(31,1);
Length = (length(DataNo));
Act_length=Length-fit;
f1 = zeros(Length,1);
dx=zeros(30,1);
dx = (Start:Fin).';
x=zeros(Length,2);
for it = 1:Act_length
    [p,S] = polyfit(dx,NormLevel(dx),1);
    f1(dx) = polyval(p,dx,fit_points);
    f3(dx)=gradient(f1(dx));
    Start = Start+1;
    Fin = Fin+1;
    dx=(Start:Fin).';
    x(Start,:)=p;
end
```

Comparing the smoothed data with the raw data using the first 1000 data points:

```
Data = [1:1000].';
f1Short=f1(1:1000);
figure
plot(Data,f1Short)
hold on
```

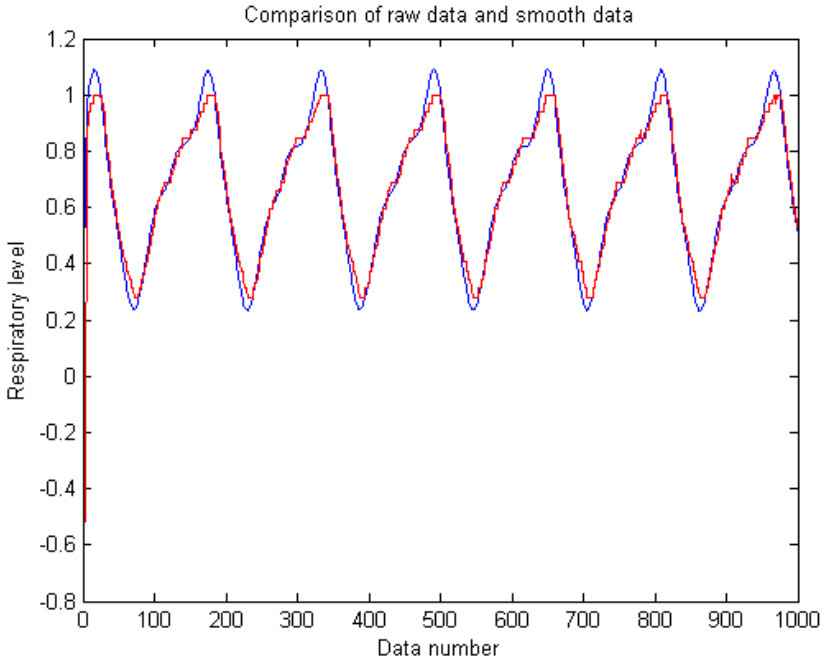

Figure A.2: The smoothed data, in blue, compared with the raw data, in red.

```
NormShort=NormLevel(1:1000);

plot(Data,NormShort,'r')
```

This is presented in figure A.2.

Generating the square wave from the smoothed data using a for loop:

```
l=length(f3);

f4=zeros(l,1);

for it=1:length(f3)

    if  f3(it)>0;

        f4(it)=1;

     elseif  f3(it)<0;

        f4(it)=-1;
```

```
    elseif   f3(it-1)<0  && f3(it)==0;
        f4(it)=-1;
    else  f3(it-1)>0 && f3(it)==0;
        f4(it)=1;
    end
end
```

Plotting the smoothed respiratory levels vs time (data number).

```
figure
subplot(2,1,1)
plot(DataNo,f1)
title ('Smoothed respiratory curve with phase wave')
xlabel('Data number')

subplot(2,1,2)
plot(DataNo,f4, 'r')
ylim([-1.5,1.5])
xlabel('Data number')
```

This graph is presented in figure A.3.

Plotting the squarewave and smoothed respiratory wave on the same axes for the first 1000 data points:

```
figure
plot(DataNo,NormLevel)
hold on
```

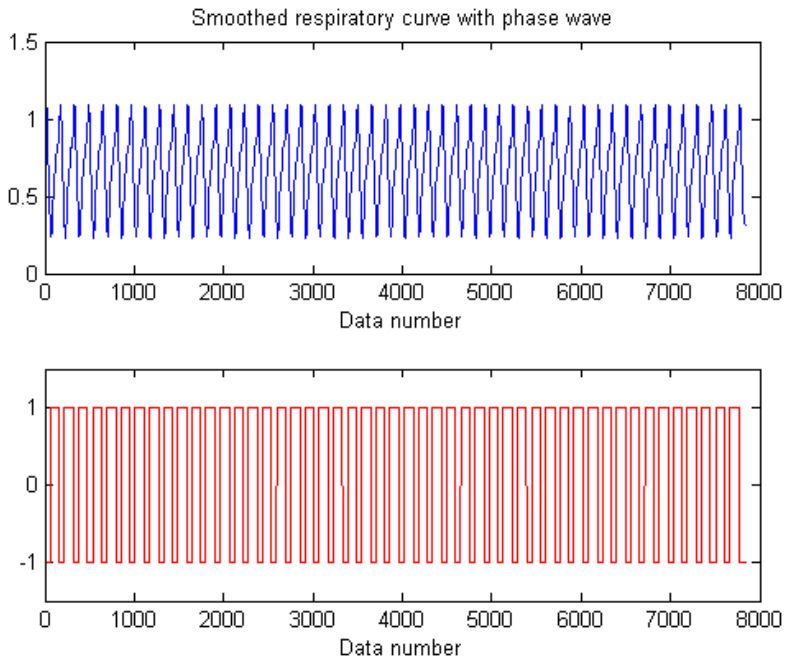

Figure A.3: A double plot showing the smoothed respiratory curve on the top graph and the square phase wave generated from the smoothed data on the lower graph.

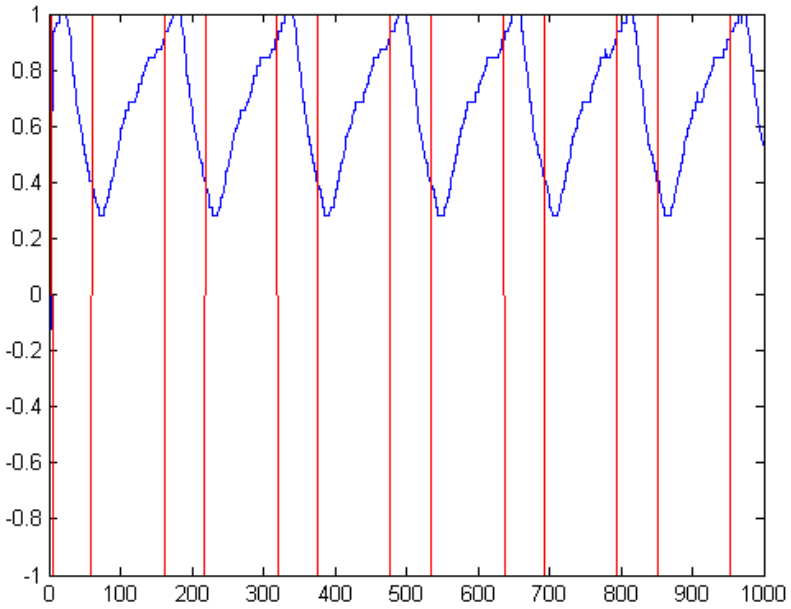

Figure A.4: Graph showing the smoothed respiratory curve with square wave superimposed on it.

```
plot(DataNo,f4,'r')

xlim([0,1000])
```

This graph is presented in figure A.4.

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